Hybrid Electric Integrated System Testbed (HEIST) and Full Scale Testing Update of the LEAPTech Wing

Presented By:
Andrew Gibson
President/Aerospace Engineer
Empirical Systems Aerospace, Inc. (ESAero)
Central Coast, California

Material Support: **Sean Clarke, AFRC, Trevor Foster, ESAero**

For:
Advanced Vertiport Capable Flight Capabilities Panel Discussion
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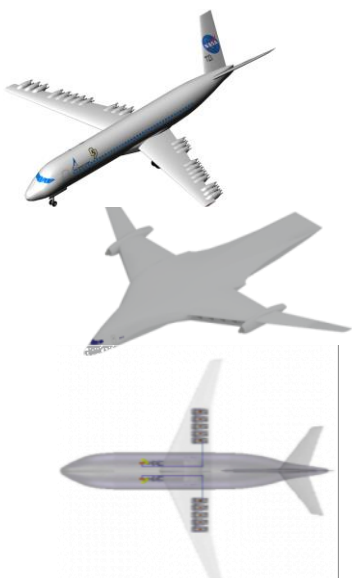
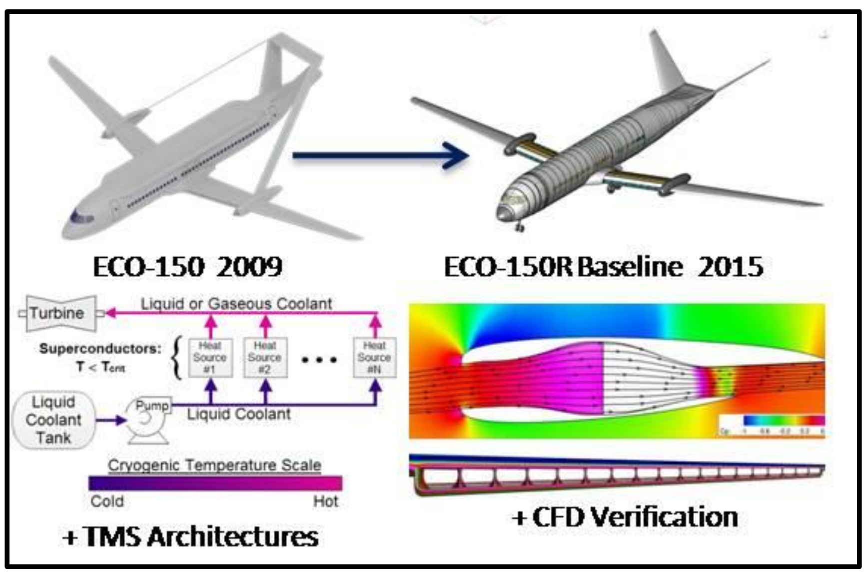
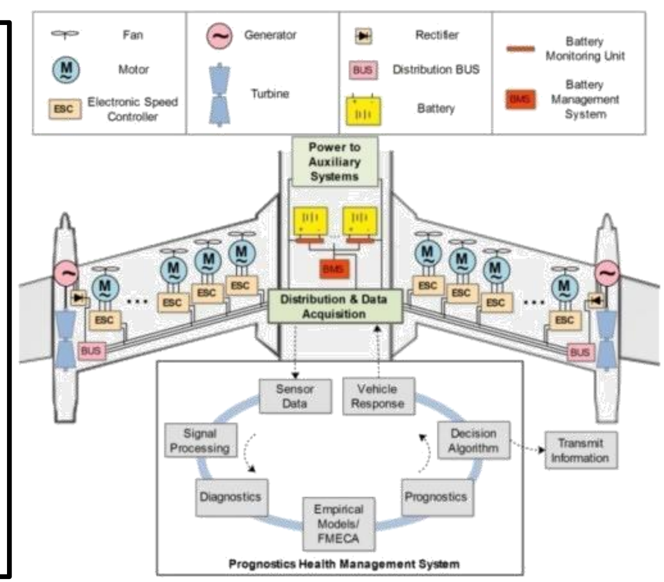
ESAero Electric, Hybrid Electric and DEP

- Working E, HE and DEP Air Vehicle Development since 2008 over 8 Phase I, 2 Phase II & 2 Phase III SBIRs and AFRL Efforts for Fixed Wing and VTOL:
  - **Multiple "Tube & Wing" DEP Concept Developments**
  - **Hybrid Helicopter/VTOL System Design, Development and Optimization**
  - **Multi-Disciplinary Electric Propulsion System (including Components) and Air Vehicle Sizing Tools (VTOL and Fixed Wing); PANTHER**
  - **Thermal Management System Sizing**
  - **Performance and Mission Analysis Methodologies and Tools**
  - **"ePHM" Prognostics and Health Management (with General Atomics IS)**
- Industry Efforts have supported AeroVironment, Boeing R&T, Lockheed Martin ADP, General Atomics SPO, Electricore Inc., and others.







AEP Roadmap to TRL 6 at Different Sizes (AVIATION ‘15)

Technologies benefit more electric and all-electric aircraft architectures:

- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

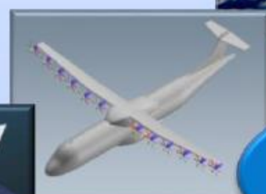
Superconducting Machines

- Turbo/hybrid electric distributed propulsion 300 PAX

>10 MW

5 to 10 MW

- Hybrid electric 150 PAX
- Turboelectric 150 PAX



2 to 5 MW class

- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX
- All electric 50 PAX regional (500 mile range)

1 to 2 MW class

- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional
- All-electric, full-range general aviation

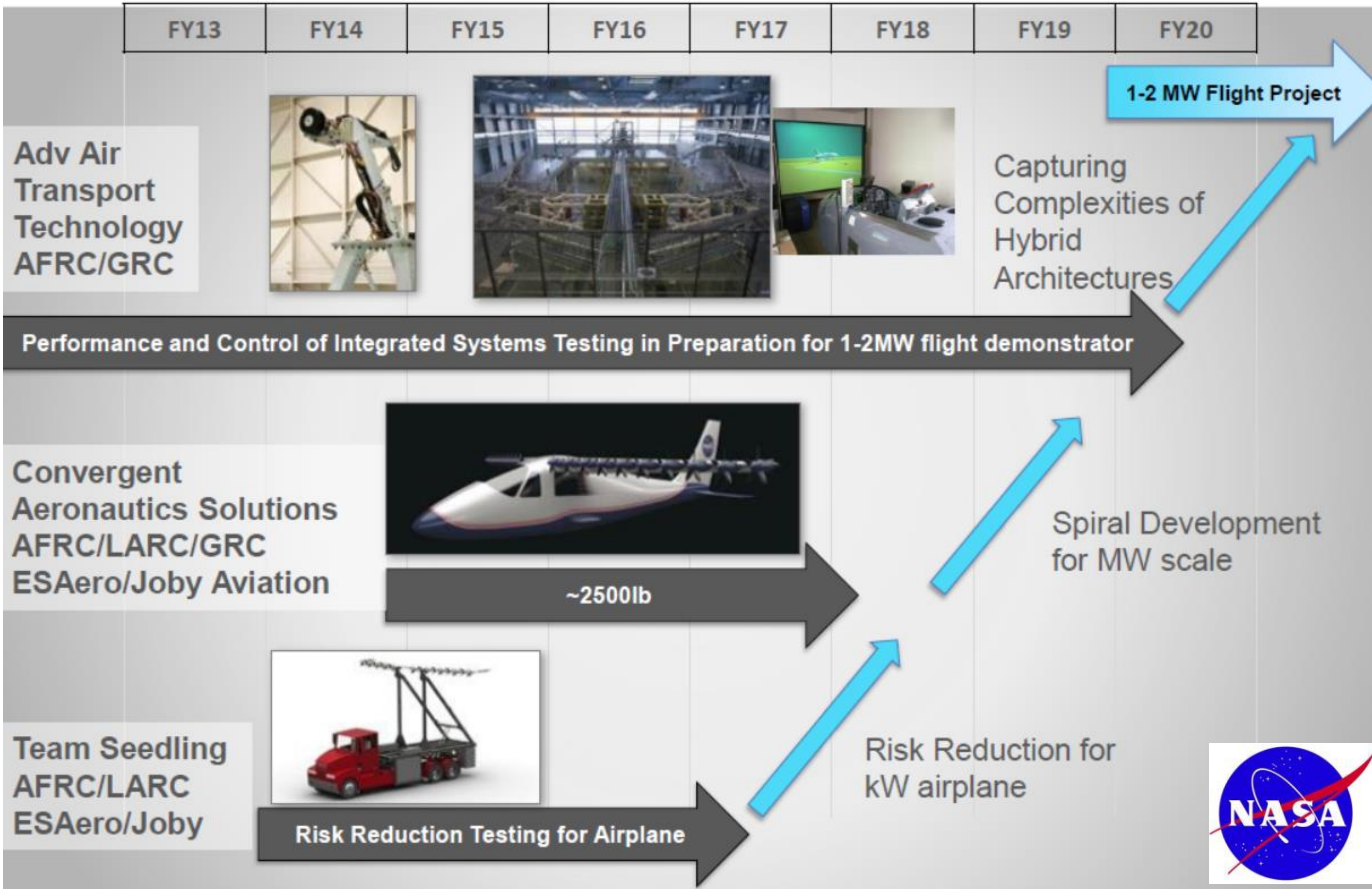
kW class

- All-electric and hybrid-electric general aviation (limited range)

Power Level for Electrical Propulsion

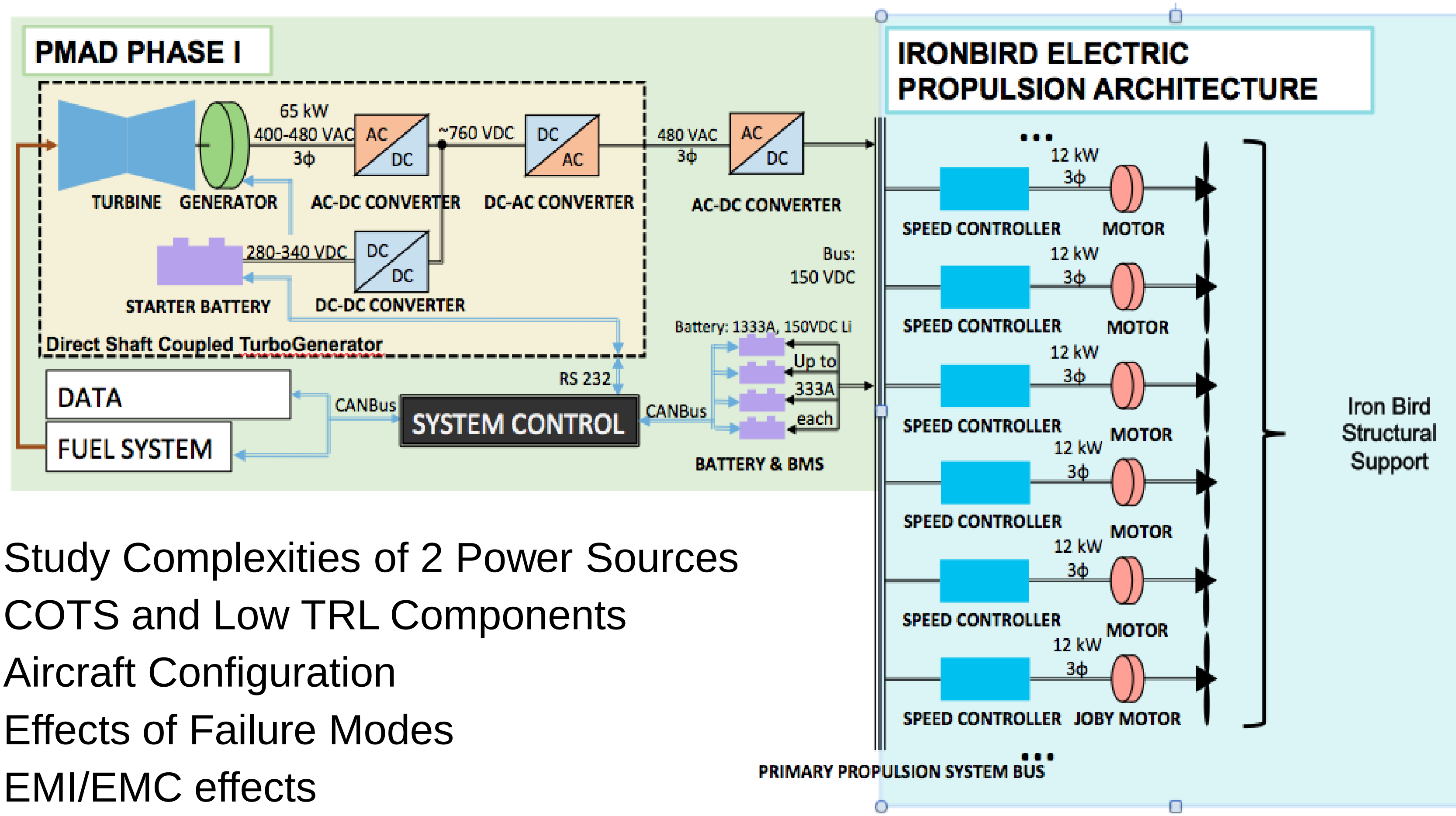
Today | 10 Year | 20 Year | 30 Year | 40 Year

Near Term Test Facilities at AFRC



Hybrid Electric Integrated Systems Testbed (HEIST)

Modular Architecture to Allow for Multiple Configurations to Enable Larger Systems to be Designed; Decoupled Energy Management



- Study Complexities of 2 Power Sources
- COTS and Low TRL Components
- Aircraft Configuration
- Effects of Failure Modes
- EMI/EMC effects
- Flight Simulator Controlled
- Verification of Failures and Modes

- Using Distributed Electric Propulsion for flight control will be dynamic!

HEIST LEAPTech Participants

- **NASA AFRC**
  - Oversight / Host
  - Requirements Management
  - Master motor controller
  - Test Execution
  - Safety Review Process
- **NASA LaRC**
  - LEAPTech lead (PI)
  - Wing aero design
  - CFD analysis
  - Structural analysis

- **Empirical Systems Aerospace, Inc.**
  - Top level engineering
  - Instrumentation
  - System Integration
  - System IOC
- **Joby Aviation**
  - Wing Manufacturer
  - Motors, motor speed controllers, propellers
  - Test Rig (truck platform) fab, force balance design

Overview - LEAPTech
Leading Edge Asynchronous Propeller Technology

32 ft Carbon Wing
18 Joby JM-1 Electric Motors
Custom Test Stand w/ water ballast
Converted Water Truck

Primary Objective:
- -Show Benefits of Propulsion-Airframe Integration
- -Validate CFD for High Speed Cruise Efficiency

Secondary Objectives:
- -Demonstrate Rapid Testing and Development in Unique Partnership between NASA and Small Business

Derivative Objectives:
- -Many Opportunities Exist

LEAPTech Instrumentation Design

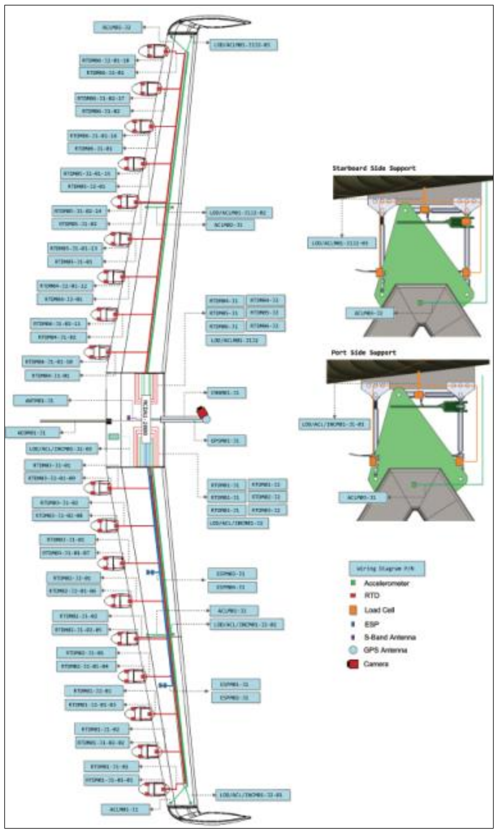
HEIST Design Phase I

Sensor 'Buy-On' Criteria

Safety Critical

Mission Critical

Technically Desired



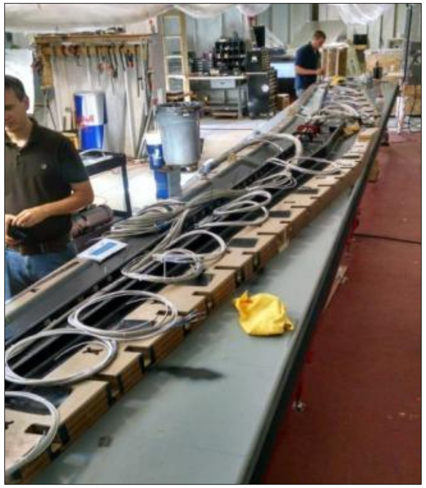
Wiring/Sensor layout

HEIST Design Phase II

Instrumentation Platform

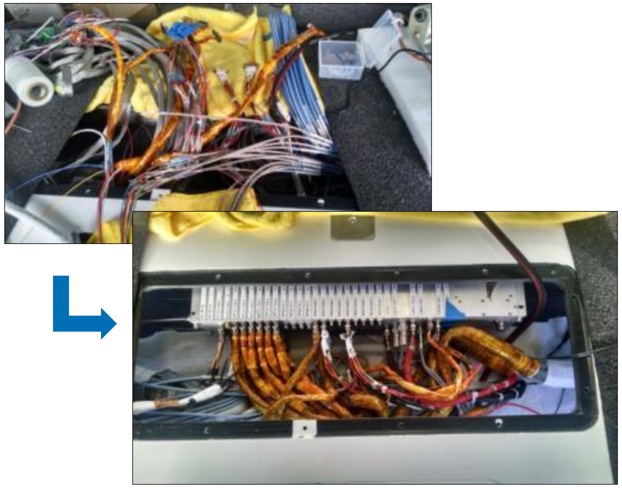
Harness Fabrication

HEIST Design Phase III



Harness Installation

HEIST Design Phase IV



Final Installation and Termination

LEAPTech Instrumentation Design

Requirements

- Aerodynamic Performance
  - Pressure strips for upper surface pressure distribution
  - High frequency pressure transducers for instantaneous pressure behind prop
  - Air data probe for airspeed and AoA
- Aerodynamic Forces
  - Load cells placed in an force balance system to acquire thrust, drag, lift, & yaw **(Critical)**
- Aeroelasticity
  - Accelerometers at multiple locations
- Temperature of Electronic Components
  - Resistive Temperature Detectors (RTDs) place in key electronics for thermal monitoring **(Critical)**

LEAPTech Instrumentation Design

Requirements Cont.

- Groundspeed
  - GPS unit to monitor ground speed
- Data Storage and Telemetry
  - Solid state hard drive for storage of video and sensor data
  - S-band antenna for telemetry
- Motor/Controller Performance
  - Motor and controller data gathered from CAN bus **(rpm, Critical)**
- Use of readily available equipment to develop a rapid proof of concept

LEAPTech Instrumentation Design

System overview

-Custom Force Balance with 7 Load Cells

-60 RTD Temperatures

-120 Pressure Measurements using ESDs and Strip-A-Tubing

-8 High Speed Transient Pressures

-3 Uni, 3 Biaxial, 2 Triaxial Accelerometers

-Air Data Probe with Alpha & Beta vanes

-2 Inclinometers

-3 HD Cameras

-GPS & S-Band Transmitter

Powered using an isolated battery pack consisting of the same capacity and chemistry cells as the primary motors

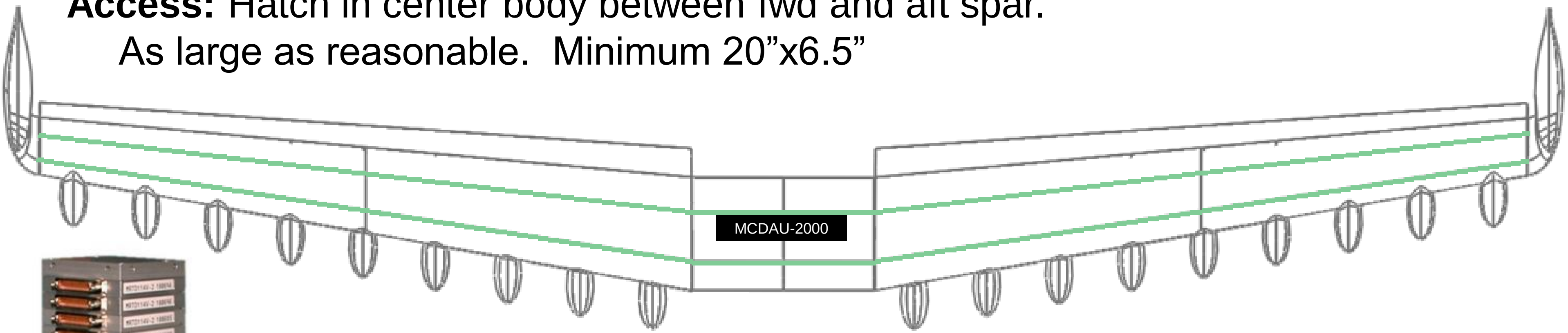
- **9S1P CALB LiFePO4 180Ah**
- **Chosen for rapid TechBrief approval**

Highlighting Some Key Sensor Integrations on the Following Slides

LEAPTech Primary Data Acquisition

TTC MCDAU-2000/F

Location: Center wing section
Mounting Requirements: Bolt to plate on aft spar
Skin Perforations: None
Cabling: Receives cabling from all other components
Access: Hatch in center body between fwd and aft spar.
As large as reasonable. Minimum 20”x6.5”



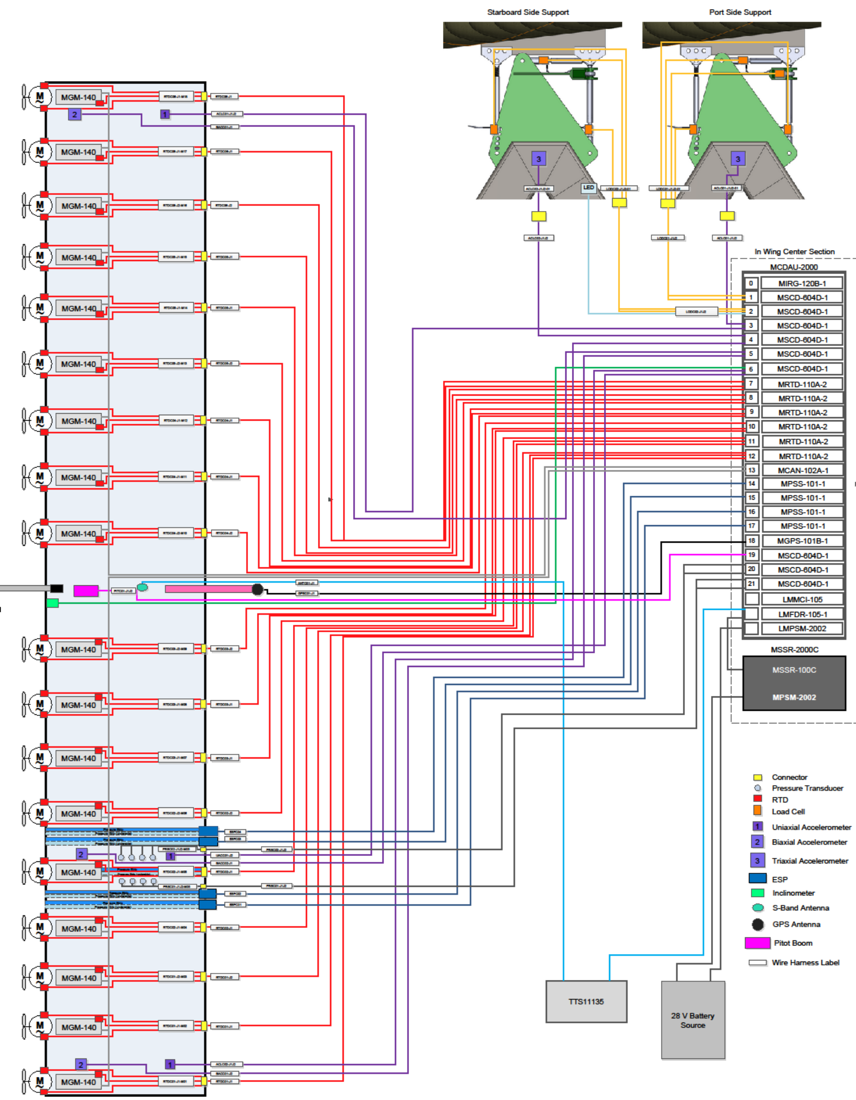
Length: 2.49”
Width: 2.63”
Height variable
Weight: variable
Data Rate: 5.0 Mbps @ 12-bit
Power: 28V @ 230w

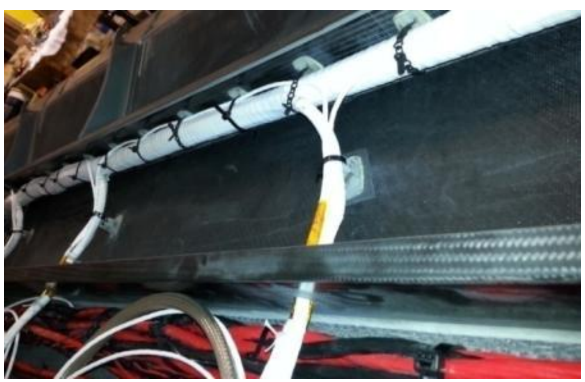
Operating temperature: -35°C to +85°C
Storage temperature: -55°C to +100°C.
Random vibration: 15grms, 20-2kHz, 10min, any axis.
Acceleration: 25g, indefinite duration, any axis.
Shock: 15g, half-sine, 11 mS, 6 shocks, any axis.
Humidity: 5-95% RH, non-condensing.
Altitude: 0 to +200,000 ft. (unlimited).

LEAPTech Wiring Harness Design

EMI Mitigation

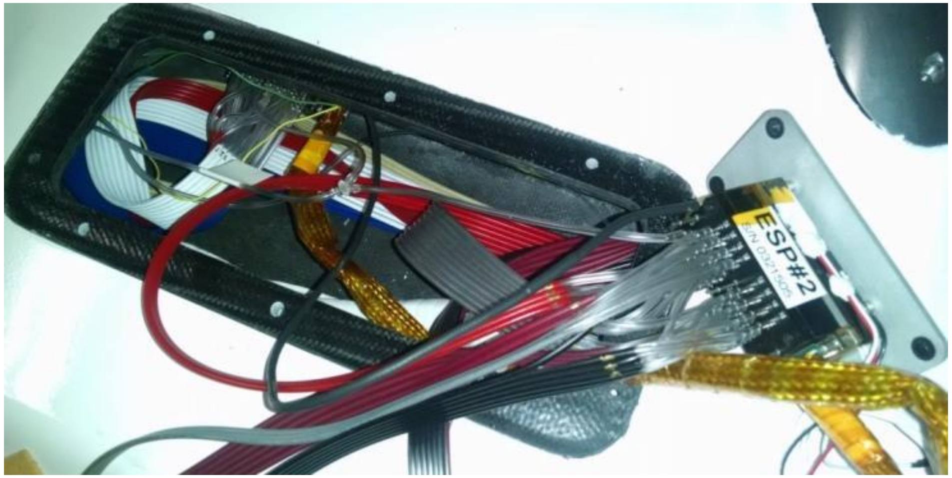
- Dual Isolated Shields
- Harnesses and Connectors wrapped to prevent electrical contact with frame
-Sensors bonded to carbon frame have fiberglass base layer



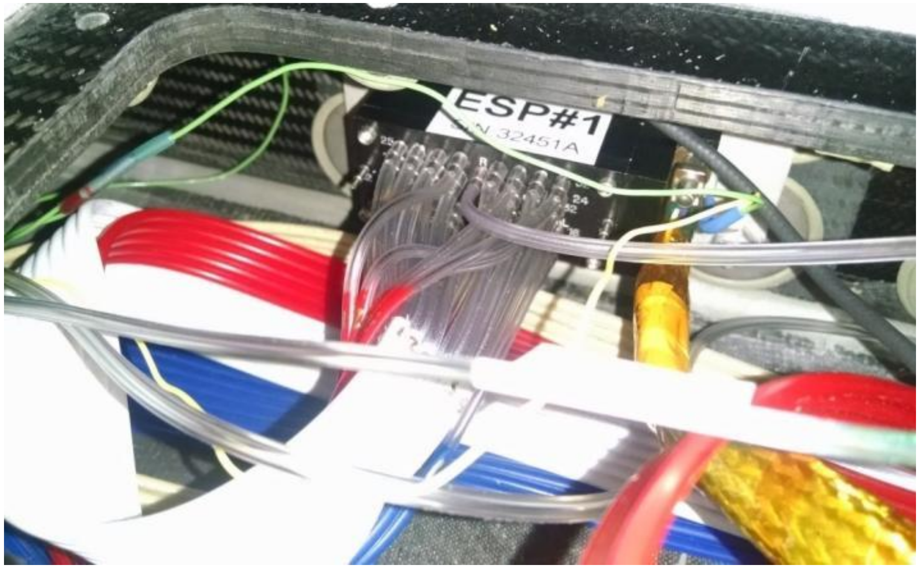


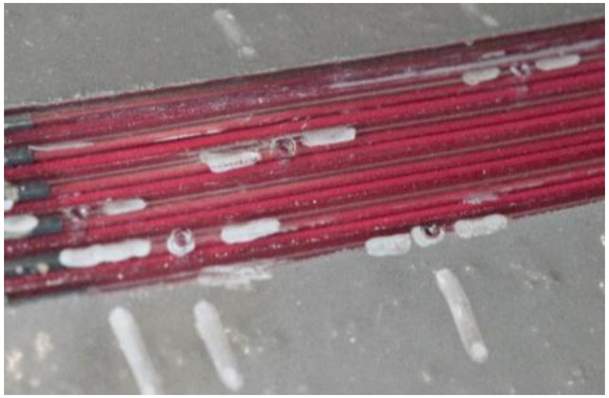
LEAPTech Surface Pressure

- ESP Pressure Scanner units to gather data for determining pressure distribution



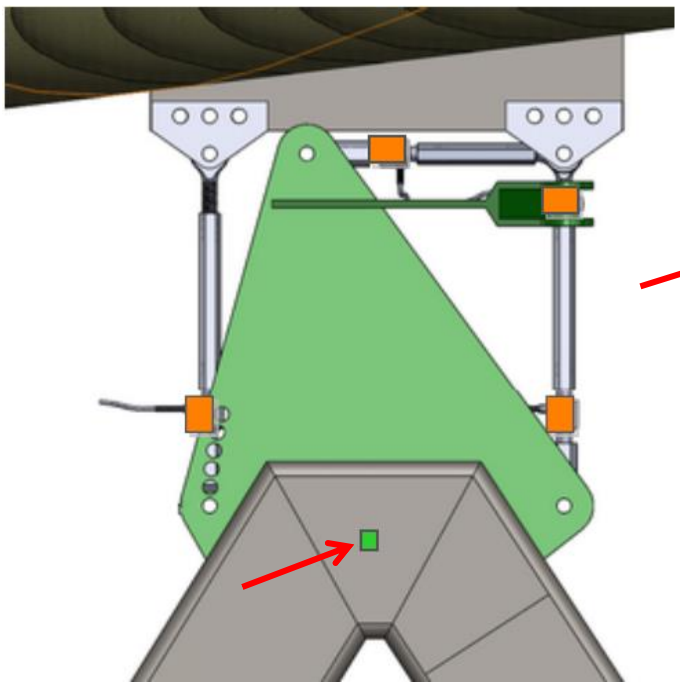
LEAPTech Surface Pressure

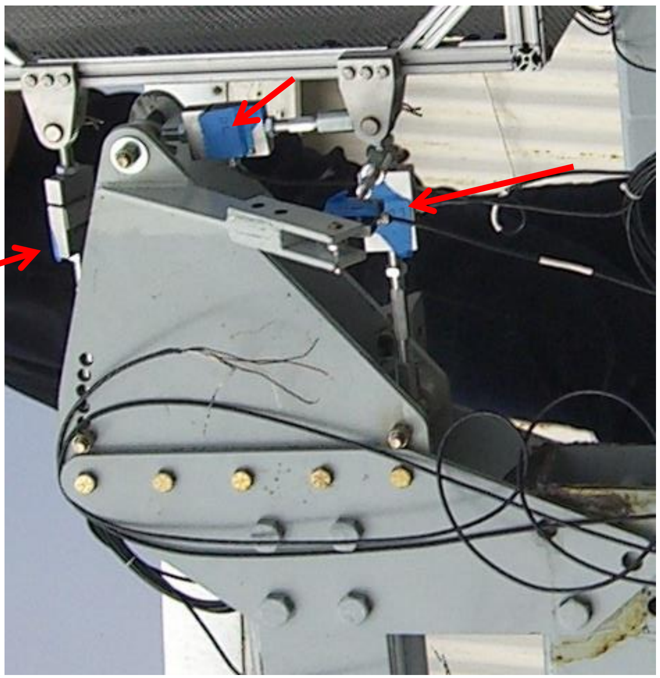




LEAPTech Force Balance

- Drag, FWD/AFT Lift
- Side Slip (STB)
- Triaxial Accelerometer
- Adjustable AoA

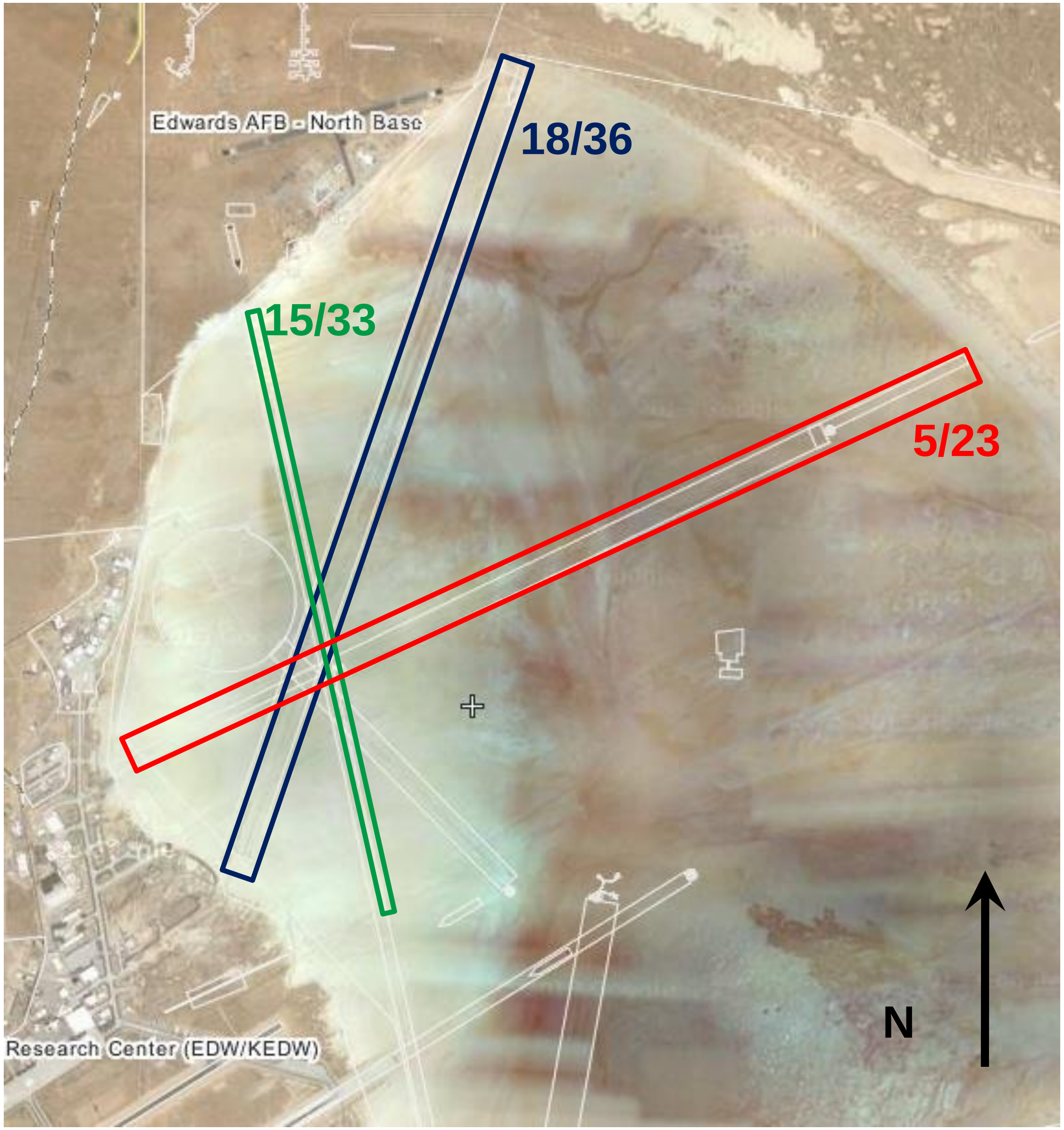




LEAPTech Operations

- Joby Power System and ESAero/Armstrong Instrumentation Data Requirements will support multiple runs per day.

- Mobile Test Platform is being Tested at NASA Armstrong on Dry Lake Bed
    - Primary Runway is 5/23
    - Backups are 18/36 and a portion of 15/33.



First High Speed LEAPTech Test

Convergent Aeronautics Solutions SCEPTOR

Scaled Convergent Electric Propulsion Technology Operations Research

PHASE I

Concurrent Activities

Requirements Definition,
Systems Analysis,
Wing System Design,
Design Reviews

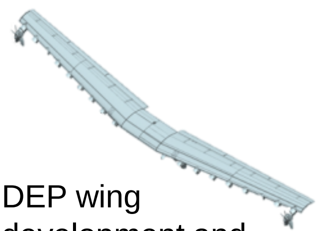
Ground validation of DEP highlift system

Flight testing of baseline Tecnam P2006T

Goals:
- Establish Baseline Tecnam Performance
- Test Pilot Familiarity

PHASE II

Concurrent Activities



DEP wing development and fabrication

Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:
- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

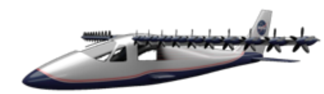
PHASE III

Flight test electric motors relocated to wing-tips, with DEP wing including nacelles (but no DEP motors, controllers, or folding props).

Achieves Primary Objective of High Speed Cruise Efficiency

More Partners TBD!

PHASE IV

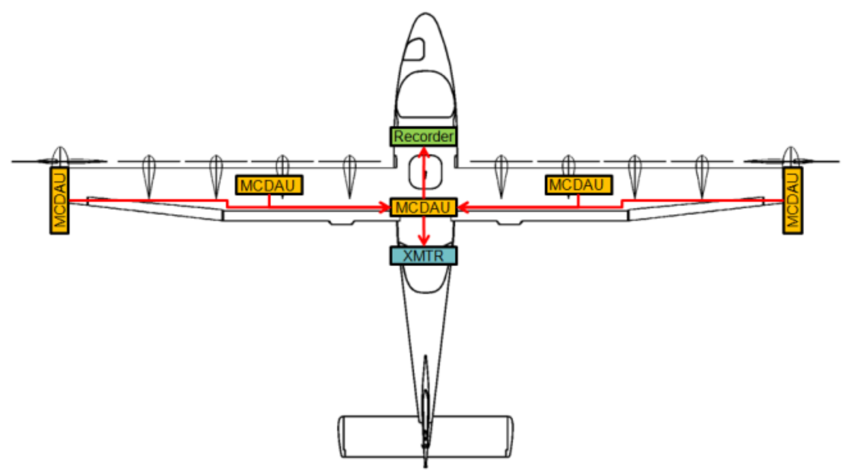


Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

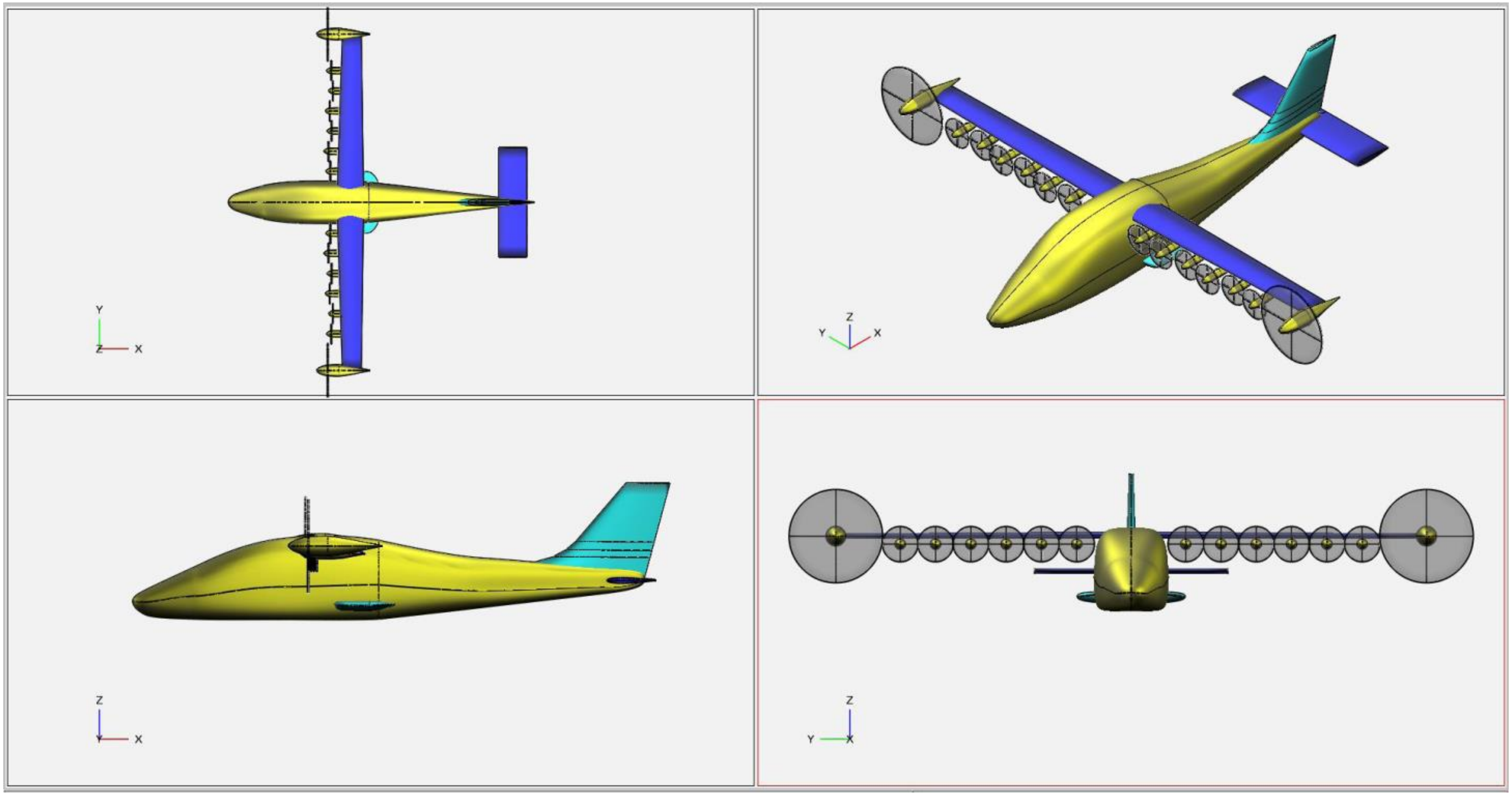
Achieves Secondary Objectives
- DEP Acoustics Testing
- Low Speed Control Robustness
- Certification Basis of DEP Technologies

Applying Lessons Learned for SCEPTOR

- Distributed DAQ system
  - More conventional
  - Reduces EMI
  - Reduces weight/volume concerns
- Connector Improvements (pressure tubing, etc.)
- Strict configuration control
- Fully detailed CAD model
- CML concept to interface with requirements
- Improved Isolation / Grounding
- System Engineering Approach



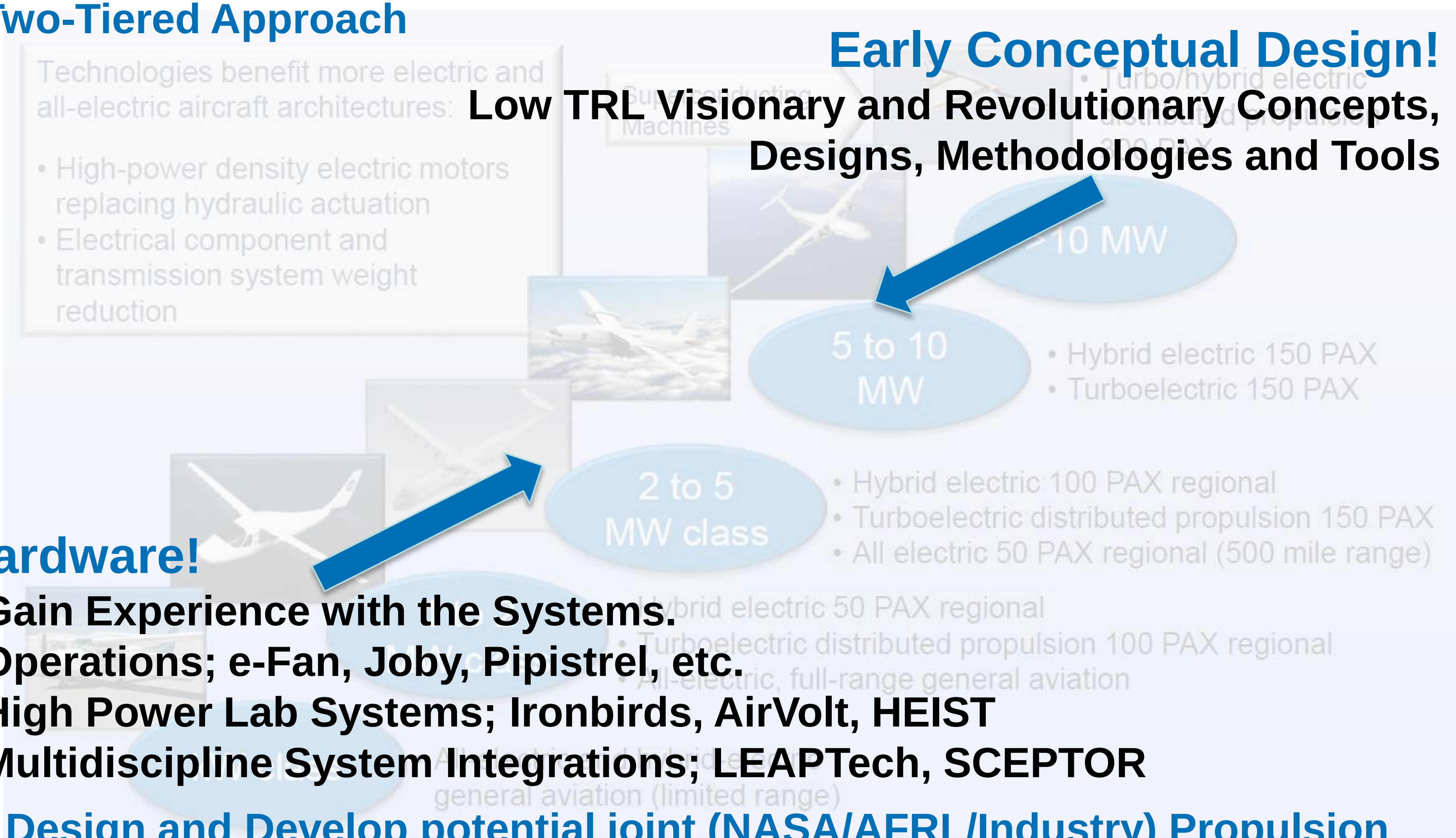
Current Design of SCEPTOR (REV3 Mod3)



Courtesy Nick Borer, NASA Langley SCEPTOR Propulsion and Vehicle Sizing IPT Lead

How will AEP Become Reality Across Vehicle Classes

Two-Tiered Approach



Early Conceptual Design!

Low TRL Visionary and Revolutionary Concepts, Designs, Methodologies and Tools

Hardware!

- **Gain Experience with the Systems.**
- **Operations; e-Fan, Joby, Pipistrel, etc.**
- **High Power Lab Systems; Ironbirds, AirVolt, HEIST**
- **Multidiscipline System Integrations; LEAPTech, SCEPTOR**

Design and Develop potential joint (NASA/AFRL/Industry) Propulsion Airframe and Thermal Integration (PATI) system demonstrations with a Spiral Development path (Roadmap).

Spiral Development

kW to MW Systems; Ground, Early Flight (CEPT) and Beyond

- **Lessons learned on Packaging DEP wiring, instrumentation and non-propulsion electrical systems in a high aspect ratio wing.**
- **EMI Concerns**
- **Thermal Management, Cooling for Motor/Motor Controller and DEP**
- **Verification and Validation of Flight Motors and Motor Controller (ePHM)**
- **Tool Validation**
- **Establish Standards for Electric Propulsion Airworthiness (ASTM F39)**
- **System Weight/Volume Restrictions**
- **Emergency Recover from DEP Motors and Wing-Tip Cruise Motor Failures (ePHM)**
- **Decoupled Energy Management; Autonomous Power Management and Distribution (PMAD) System Controller(s) with Multiple Power Sources; Coupled to Flight Control System.**

Transformative VTOL Future Call for Papers AVIATION ‘16

- **Air Transportation Integration & Operations - Unique and/or Transformational Flight Systems**
- **Transformational Flight Program Committee**

“Technical Papers are requested relating to Advanced Manned/Unmanned Concepts, Electric Propulsion Integration and Component Technologies, Autonomy/Self-Flying Aircraft/Simplified Vehicle Operations, and On-Demand Mobility Emergent Aviation Market Studies. Papers are also requested on any topic of interest relative to V/STOL, including Design, Analysis and Test. This includes STOL Aircraft and VTOL Aircraft, regardless of Propulsion System Type”.

- **Advanced/Transformational Aircraft Concepts**
- **Electric Propulsion Integration and Component Technologies**
- **On-Demand Mobility Emergent Aviation Market Studies**
- **V/STOL Aircraft Design, Aircraft Analysis, and Ground and/or Flight Test**
- **Transformational System Design, Development, Analysis, Materials, Operations and Support**

Thank You!

E|S|AERO

andrew.gibson@esaero.com